INTRODUCTION TO FEASIBLE INNOVATIONS IN SIDE IMPACT SAFETY

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ABSTRACT

"A more synergistic view or approach to motor vehicle safety design aspects is needed." (Robbins – SAE-Paper 970488).

The aim of this work is to indicate some feasible innovations that may lead to a better side impact protection, pointing out some aspects that can be developed thoroughly within the corresponding settings and using the appropriate resources. The mentioned innovations will be analyzed from a general and synergistic point of view, using basic engineering and physics principles, and considering the following:

- simulations will be performed using a simplified model consisting on a single-mass/inelastic-spring system.
- some physiological premises will be considered (such as "direct impacts should be avoided at any place of the organism"; "high accelerations can be sustained during short periods of time"; etc.).
- the bases of safety in road crashes will be established, namely "control the perfect operation and use of the safety devices"; "maintain the structural integrity of the occupants' vital volume"; "absorb the whole kinetic energy both of the vehicle and of the occupants"; etc. Subsequently, these bases will lead to determining the main functions that the compartment, external/internal structure and restraint devices should perform to enhance the safety they offer.
- the protection offered by current safety devices will be analyzed, segmented into three groups (pre-impact, impact and post-impact).

All of this will allow the discussion of some feasible innovations leading to better side impact protection. Finally, considering the inherent reluctance to introduce valuable safety innovations into current automobiles (e.g.: four-point seatbelts) a strategy to perform this in a successful manner will be discussed.

INTRODUCTION

"Near side crashes have higher serious injury and fatality risks as compared to all crashes". (Samaha/Elliot – NHTSA side impact research: motivation for upgraded test procedures – Paper 492 18th ESV Conference).

Every year more than a million people die and dozens of millions must bear some kind of permanent impairment as a consequence of road crashes (1). The vast majority (90%) of the victims belong to low-income or middle-income countries, where most of the fatal crashes involve pedestrians, cyclists or motorcyclists. Moreover, it can be argued that the most frequent road crash involving only automobilists is the one where two vehicles sustain a frontal head-on collision. Yet, side impacts are both a common and a dangerous phenomenon, involving for instance, 20% of fatal crashes and 30% of injury crashes in the United States (2). Some of the highlight characteristics of side impacts are the following (3):

- most side impacts involve vehicles travelling perpendicular to each other.
- the struck car generally is travelling slower than the car that strikes it.
- the struck car generally has a low Δv (velocity change).
- the time epoch for side collision is slightly greater than that of a frontal collision.

Before going on, it can be argued that a driver travelling on his automobile has an intrinsic tolerance to injury which is opposed to a variable "injury potential". On one hand, the injury tolerance is defined by:

- an inherent biological tolerance to accelerations and direct impacts.
- the protection provided by his vehicle.
- the protection provided by the road infrastructure.
- an emergency environment that will assist him in case of a road crash.

On the other hand, and as far as this paper is concerned, the "injury potential" depends on the mass and speed of the striking vehicle; that is to say, on the kinetic energy of the impact. As it is known, speed has greater influence than mass in the value of the kinetic energy of an object: while mass has a directly proportional influence on this physical dimension, speed has a directly quadratic influence. Moreover, when compared to frontal impacts, it can be argued that side impacts happen at lower speeds, therefore bearing lower levels of "injury potential".

EXAMPLE BOX 1

Estimated average travel speed in fatal crashes in the United States according to their manner of collision

An analysis using the data available at Fatality Analysis Report Systems (FARS) allows to estimate the average travelling speed of fatal crashes for the years 2002-2003 in the United States, according to their manner of collision. Two of the available categories were considered: on the one hand, "front-to-side, right angle (including broadside)" was used to estimate the average impact speed of perpendicular side impacts; on the other hand, "front-to-front (including head-on)" was taken to estimate the average speed of frontal impacts. The results of the analysis show that in the United States, in the considered years, the average impacts speeds for the mentioned impacts were:

- *61 km/h for perpendicular side crashes.*
- *79 km/h for frontal crashes.*

The frequencies for the travel speed for both types of crashes can be observed in the following figures:

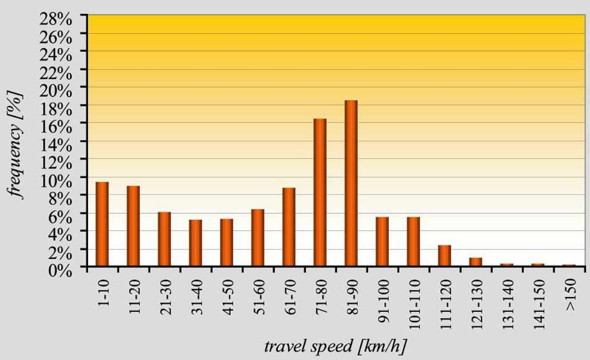


Figure 1. Frequency of registered fatal "front to side, right angle" crashes according to their travel speed in the United States for the years 2002-2003.

Source: reference 4

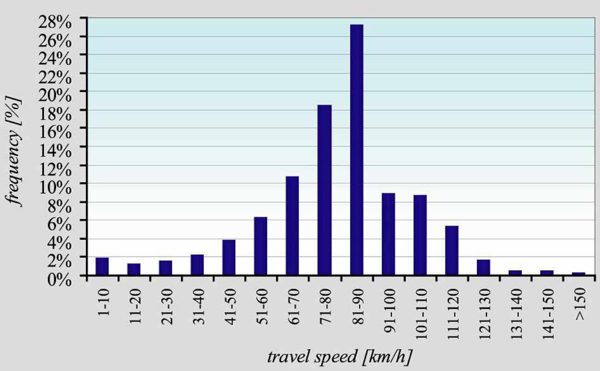


Figure 2. Frequency of registered fatal "front to front" crashes according to their travel speed in the United States for the years 2002-2003.

Source: reference 4

From both figures it can be deduced: firstly, regarding side impacts, most fatal crashes involve speeds that stretch out between 1 km/h and 90 km/h with a larger concentration in the range 70-90 km/h; secondly, in the case of frontal impacts, the majority of fatal crashes stretch out in a narrower range, between 60 km/h and 110 km/h, with a larger concentration, again, in the range 70-90 km/h.

It is worth mentioning that for side crashes there is a greater density of fatal crashes in the lower speed range, which gives a hint of an issue that is going to be discussed in the following pages: since equal speeds bear approximately the same level of "injury potential", when considering the available safety devices acting in frontal and side impacts, a higher proportion of fatal injuries at lower speeds may imply lower levels of protection as regards side crashes.

For a better understanding of the aspects of crash severity involved in a side impact, an example of an automobile sustaining a side impact against another vehicle will be analyzed and compared to frontal and rear crashes. The following figure sketches the general simplified scheme that is considered for the modeled automobile:

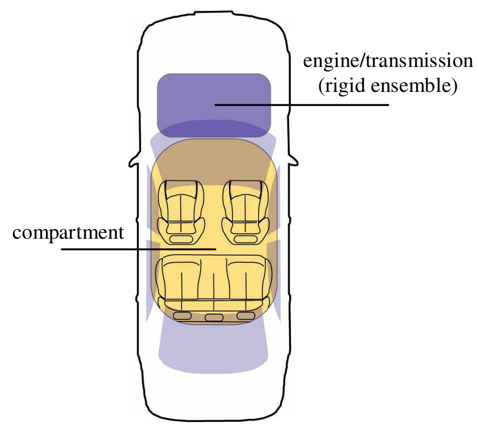
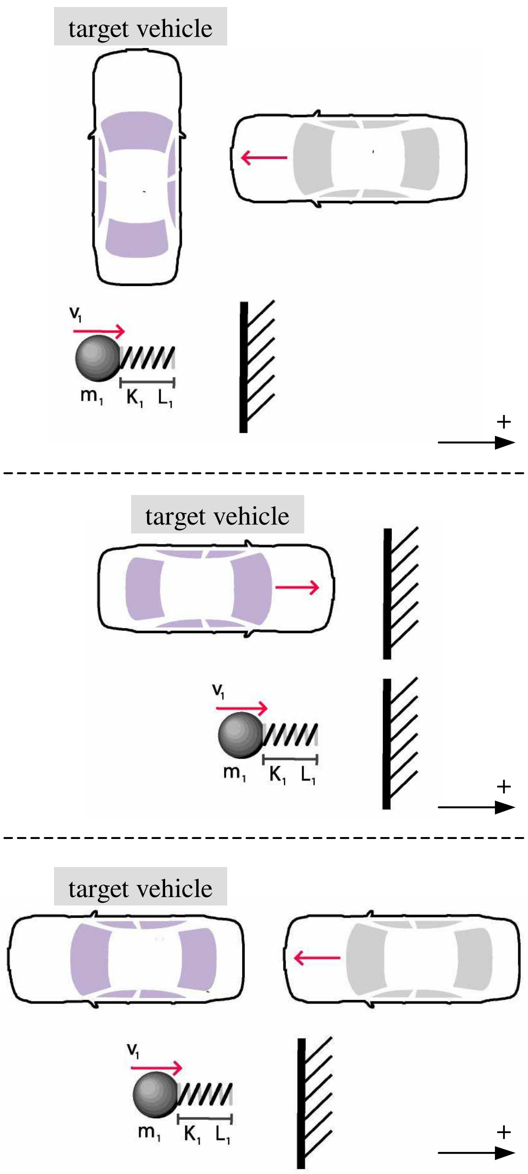


Figure 3. General simplified scheme used for the modeled vehicle.

The conditions that are going to be modeled are that of a medium-size car weighing 1.500 kg that in the case of the side impact, is struck perpendicularly on its side by another similar vehicle while stopped; in the frontal impact, it strikes a fixed object; and in the rear impact, it is struck from behind by another similar vehicle while stopped. In order to do so, a series of simplifications should be considered, namely: one dimension movements; reference of coordinates in the center of mass of the target vehicle; and the use of a system formed by a single mass and an inelastic spring which, according to what many experts agree, is the model for the description of the behavior of an automobile in a crash that suits properly the purpose of this work (5). The general models for the three types of road crashes that are going to be analyzed can be described as follows:



(m_1 = mass; K_1 = stiffness coefficient;
L_1 = length of spring; v_1 = speed)

Figure 4. Models for a side perpendicular collision between two similar vehicles, a frontal collision against a fixed object, and a rear collision between two similar vehicles, respectively.

It must be remembered that although the physical phenomena that happen in a traffic crash are extremely complex to be accurately described, the considered mathematical models will allow to predict the general behavior of the automobile, with an appropriate precision for this paper, to assess the reasons why it is alleged that near side crashes have higher serious injury and fatality risks as compared to all crashes. In this regard, it can be argued that the side external structure of a vehicle has an inferior capacity of absorbing kinetic energy than the frontal or rear external structures, and passengers are much closer to the point of impact. Therefore, in a lateral collision the vehicle structures intrude into the compartment more readily, more often and more severely than they do in frontal and rear crashes of equivalent kinetic energy.

A further analysis of this last statement can be done by completing the simplified models for each of the manners of collision that are being compared. To begin with, the lengths of the inelastic springs must be defined. The following figures will show the structures of the modeled vehicle that are destined to absorb the kinetic energy of road impacts, their estimate lengths, and their relative position in regards to the occupants compartment:

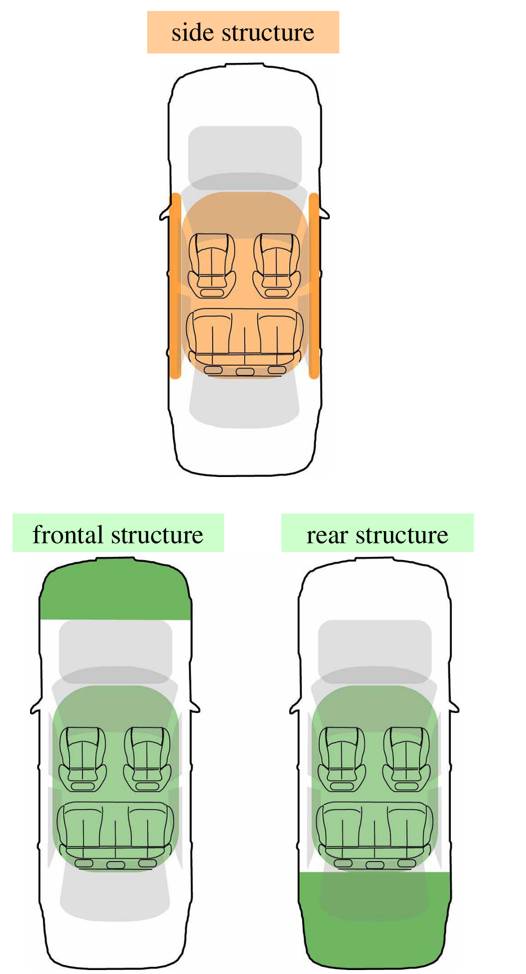


Figure 5. External structures of the modeled car which are destined to absorb the kinetic energy, their estimate length and their relative position to the occupants compartment.

This last figure allows a visual review of the mentioned issues regarding side safety, specially the one that states that passengers are much closer to the point of impact in the case of a side crash when compared to frontal or rear ones. Nevertheless, to complete the model so as to be able to evaluate the capacity of each external structure to absorb the original kinetic energy, the last characteristic of the inelastic springs must be considered: their stiffness coefficients. It is the intention of this paper to use approximate values, since there is a great difference between the various makes and models. Therefore, the numbers that are going to be used in the case of the frontal structure are based on the consulted bibliography (6, 7). As regards the rear and side structure, it is considered that they bear stiffness coefficients that are half the one of the frontal structure, since they lack in the frontal rails that provide an additional reinforcement to the structure. It is important to highlight that the estimated values should be considered only as a result of a series of theoretical and simplified assumptions, in order to perform some analysis that will help to understand better the issues discussed. Hence, taking into consideration both the recently named aspects and the length estimation derived from Figure 5, the values for the inelastic springs that are going to be used are the following:

Table 1.
Estimated characteristics of the inelastic springs of the lateral, frontal and rear structure of the modeled vehicle.

protection structure	spring length [m]	stiffness coefficient [N/m]
lateral	0,15	612.500
frontal	0,75	1.225.000
rear	1,10	612.500

Now that the models are complete, the amount of kinetic energy that each structure can absorb will be analyzed. Since the considered structures behave as mass-spring systems, the maximum kinetic energy that can be absorbed is going to be equal to the maximum potential energy that the springs can store:

$$E_p = \frac{1}{2} K.L^2$$

(E_p = potential energy; K = stiffness coefficient; L = length of spring)

Thus, using the values indicated in Table 1, the maximum kinetic energy that the modeled structures can absorb in an impact is:

- 345 kjoule for the frontal structure
- 371 kjoule for the rear structure
- 7 kjoule for the side structure

The following figure compares such results:

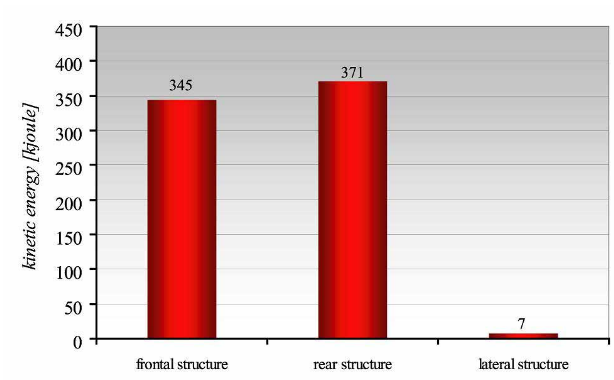


Figure 6. Maximum estimated capacity of absorption of the kinetic energy of an impact for the frontal, rear, and lateral structure of the modeled vehicle.

Once again it must be remembered that the shown values may not reflect the exact response of an actual automobile, and are only intended as rough, theoretical approximations to indicate the great differences in managing the kinetic energy of an impact for the various structures; a key issue that certainly defines whether a car occupant survives undamaged or not a road crash. When kinetic energy is not properly managed, extremely high acceleration phenomena can manifest, exposing automobilists to levels of accelerations that are beyond their biological tolerance. Even worse, when part of the original kinetic energy is not absorbed, it may lead to compartment intrusions and thus, to direct impacts to the motorists. Hence, deeming the aspects recently analyzed, it can be argued that the structural protection offered by modern vehicles as regards side impacts is far less efficient (given crashes of equivalent kinetic energy) than the one offered in frontal or rear impacts.

Moreover, it can be stated that these days automobiles are every time faster, heavier, and more powerful, most of them allowing stable driving at speeds that a few decades ago only sports cars permitted. Furthermore, circulation speeds are expected to be increased in most countries since:

- many drivers prefer to travel at very high speeds, exceeding by far the legal limits (apart from the fact that human beings have a serious fascination for speed, the dangers related to high speed circulation are not completely understood; in this context some people even argue that it is safer to circulate at high speeds because some advantages are enjoyed –e.g.: it takes less time to ar-

rive to destination, so drivers are less exposed to traffic dangers–)
- both the drivers and the system have proven to be unable to maintain the circulation speeds below legal limits.

As a result, automobiles structures are constrained to manage every time higher levels of kinetic energy, that is to say, to efficiently respond to situations that bear every time higher "injury potential".

To conclude, this paper does not propose a milestone technological innovation nor it states that the actions taken so far in the field of side impact safety have been incorrectly directed. Instead, it provides an additional general review to the feasible innovations (consisting mainly either in improvements or in the reengineering of existing devices) that can lead to a more efficient protection in the case of a side road crash. It is also its intention to encourage everyone who is or will be dedicating great amounts of efforts to diminish the burden of traffic crashes –and who believes that the best way to do so is by a general and synergistic approach– indicating some innovations that, developed thoroughly within the corresponding settings and using the appropriate resources, may provide the conditions where the human body is capable of undergoing a side road crash without serious or fatal injuries.

PHYSIOLOGICAL PREMISES

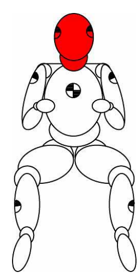
"Intrusion is either a major or contributing cause to most near side collision injuries" (Hyde – Crash injuries– how and why they happen).

The incredible and enormous biodiversity of the human beings is of such extent that the experts have not been able yet neither to understand completely how injuries happen nor to determine with precision the biological tolerance to direct impacts and acceleration phenomena. In the preface to the "Handbook of human tolerance" of the Japan Automobile Research Institute (1976) one of its authors pointed out that the current state of the field of biomechanics of trauma can be compared to the state of the celestial mechanics before Kepler: it is composed of a multitude of measurements and experimental data that lacks in unifying theories that would be able to predict the outcome of a new situation. In this way, the alleged tolerances of the human body are based almost exclusively on empiric results, or are elaborated from tests using dummies or other mechanical devices which do not represent accurately the response that a human body would show to the given situation. In the better of cases, they do represent it only for a certain percentage of the population (7). Therefore, what follows is only an overview to the topic, aimed at making a general approach to some relevant aspects for the upcoming discussions. As said before, kinetic energy management is vital. Residual kinetic energy may provoke violent acceleration phenomena or severe intrusions that can inflict direct impacts to the automobilists. Hence, considering that the mechanics of a road crash necessarily imply the combination of changes of speed and deformations, some basic assumptions must be made so as to define the lesser evil. So, the questions to answer are, among others:

- is it preferable to exert high levels of acceleration upon an automobilist without exposing him to direct impacts? Or is it the other way around?
- are side-to-side movements of the neck more dangerous than rear-forward ones?
- can a direct impact on one part of the body affect vital organs situated away from the point of impact?

These and other vital questions are not herein responded thoroughly, since the intention of this paper is to analyze some aspects of road crashes considering the available information as a general guide. Yet, some assumptions are made in order to deduce the bases about safety in side impacts. These assumptions must be confirmed by the corresponding experts using the appropriate resources. To begin with, the injury mechanisms are concisely described as follows (7).

Head, neck and spine injury mechanisms



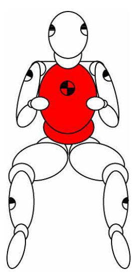
Injuries in these vital organs are devastating, and generally lead either to the automobilist's death or to various forms of permanent physical impairment.

Direct impacts in the head can severely affect the brain and most of the sensory organs located within it. It is both probable and frequent to observe brain harm without any cranium fracture, since the relative movement between the rugose base of the cranium and the brain can torn blood vessels and nerves entering and exiting the head, causing cognitive and behavior deficiencies as well as memory disorders. Regarding sensory organs, smell, taste, sight, sound and balance can be affected by direct and indirect impacts (even minor ones) to the cranial nerves or to the organs situated in the head.

Compression forces in the neck can provoke fractures in the first vertebrae of the vertebral column damaging the arteries that circulate through them. This damage seriously compromises the blood supply to the brain; besides, tears of the vertebral arteries are often fatal. Tension forces caused by hyperflexion or hyperextension (namely when whiplash, or severe flexion of the neck take place) generate cervical sprains with the potential to provoke fatal injuries, or functional disabilities which may arise years after the crash took place.

Finally, direct impacts can also damage the spinal cord severely; furthermore, this type of injury cannot be treated medically, as no therapy results in recovery. Crash injuries involving the spinal vertebrae are often violent events in which the flexed spinal column is additionally subjected to coupled forces of rotation and lateral bending. Damage to the lower section of the spinal cord may derive in paraplegia or serious urinal and sexual problems. Injuries above the lumbar region add breathing disorders to the mentioned consequences. Lastly, injuries in the higher section of the spinal cord frequently derive in quadriplegia, with a total loss of many essential body functions.

Abdomen and chest injury mechanisms

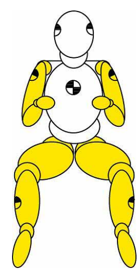


Injuries in these vital organs are also devastating.

Injuries in the abdomen are caused when suffering a direct impact, with the aggravating circumstance that as it is an incompressible hydraulic cavity, a blow in a sector of the abdomen can generate a serious damage in another place, away from the impact point. As regards the organs that can be affected by a direct impact in the abdomen, the peritoneal cavity gathers many vital organs and glands such as the liver, the spleen and the pancreas; except for the mouth and esophagus, the entire digestive tract is contained within the peritoneal cavity or is partially covered by peritoneal membranes; also, the abdominal aorta and vena cava are located on the posterior wall of this cavity. Most of these organs are soft and crumbly, and a great quantity of blood circulates through them (specially through the liver), so their damage often results in losing the organ or in catastrophic bleeding.

In the case of the chest, most of the organs residing within it –as the heart and the lungs–, or transiting it –as the esophagus, and, again, the aorta and the cava– are vital, so any damage to them has the potential to generate very serious or fatal injuries. It is worth mentioning that injuries to this body region may be fatal in the short-term, but they bear no consequences in the long-term (precisely the contrary to what happens with the extremities, as it will be discussed). Damage to the chest can provoke either respiratory or circulatory complications. As regards the first ones, direct impacts may injure the intrapleural membrane, affecting air movement into the lungs, and resulting in death if not treated immediately. Moreover, any injury that affects the capacity of the diaphragm to contract or that damages lung tissue may lower the quantity of oxygen in blood (as a result of deficient respiration) affecting other organs that are sensitive to oxygen insufficiency. Brain tissue is specially sensitive to this kind of insufficiency, so concurrent lung injuries directly and adversely affect brain injuries. As regards the circulatory complications caused by direct impacts, they are also extremely harmful. There are estimations that state that only 30% of the victims of injuries to the heart or main blood vessels survive long enough to be able to receive medical attention.

Lower and upper extremities injury mechanisms



Injuries in the extremities (arms and legs) may be seldom the cause of death in a road crash, but they are surely a major –if not the main– cause of permanent physical impairment. Injuries in these organs are generally a consequence of direct impacts, and while they do not involve particularly risky situations, it has to be taken into account that the movement of fractured bone fragments generates serious damages to the muscular tissues and massive internal hemorrhages that, unless treated expeditiously, can provoke severe injuries.

It is worth mentioning that the extremities are not restrained in any case, and that even in the event of crashes at moderate speeds they are liable to strike the interior surfaces of the vehicle. Moreover, the upper extremities can also strike the body of the other occupants of the car, exposing the latter to potential damage –specially in the head–.

Impact and acceleration resistance

First of all it can be highlighted that in a road crash there is commonly a combination of direct impact and acceleration phenomena. Most body organs are viscous and gelatinous, so direct impacts generate relative movements and consequent deceleration processes. On the other hand, restrain devices apply a certain amount of force in localized parts of the body, as in the case of the thin strip of the seatbelt fastening the chest. These restrain actions combine a deceleration process with a determined degree of pressure that, depending on the severity of the road crash, can lead to direct impacts. Hence, the question whether it is preferable to exert high levels of acceleration upon an automobilist without exposing him to direct impacts, hides a tricky issue, for the reasons recently explained. In this regard, it can be argued that direct impacts in most regions of the human body seriously compromise vital organs, and bear the potential to inflict very serious and fatal injuries. The parts of the human body that should be particularly protected from direct impacts are: the head; the neck and spinal cord; the chest; the abdomen.

On the other hand, empirical evidence demonstrates that human beings can be exposed to high levels of accelerations with a resistance that diminishes as the time of exposure to it increases, and that there are senses and directions more favorable than others. In other words, it is possible to survive without serious damage from extremely high levels of accelerations given that: firstly, the time of exposure remains below extremely short periods of time; secondly, the direction of the movement is transverse to the body, and in the sense of pushing the person backwards; and thirdly (and the least common of all), the process is not combined with direct impacts. The following figure shows the direction and senses that may damage seriously a human being that is being accelerated, and that coincide with frontal and lateral impact movements (7):

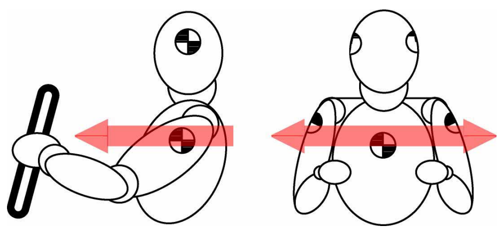


Figure 7. Most dangerous directions and senses for acceleration processes.

Furthermore, it can be stated that when it comes to acceleration resistance, a sudden acceleration of the head can lead to hyperflexion or hyperextension of the neck, and that the most harmful movements are the following (7):

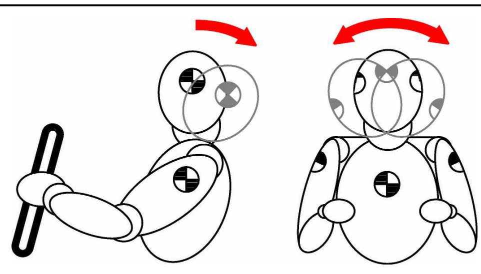


Figure 8. Most dangerous directions and senses for acceleration of the head processes.

To conclude, as far as this paper is concerned, the following figure summarizes the conclusions extracted from the concepts mentioned above (instantaneous changes of speed, which were not previously mentioned, are considered as phenomena that involve extremely high levels of acceleration over a period of time that tends to zero, are associated with elastic-type crashes, and are deemed to be more dangerous than normal deceleration processes):

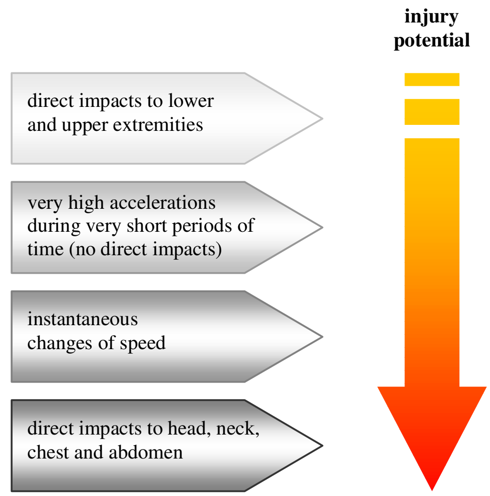


Figure 9. Alleged risk factors according to their injury potential when considering a road crash.

EXAMPLE BOX 2

***Case story of a crash involving harmful direct impacts without significant variation of speed** (8)*

In June 1993, a driver was struck by another car, thus losing control and hitting the guardrail. As this happened, the right side of the car rode up onto the guardrail, stayed on it some 12-24 meters, and then fell back to the ground, coming to rest in the emergency lane. During the incident, the rear occupant, a 31-year old female, flexed forward and to her right, and sustained head contact against the front seat. The Δv of the frontal impact was estimated at between 8 km/h and 16 km/h, and the vertical acceleration at between 10 g and 20 g. As a result of the impact, the female rear occupant sustained an L1 (lumbar vertebrae) fracture with anterior wedging, resulting in paraplegia.

BASES OF IMPACT SAFETY IN SIDE ROAD CRASHES

"In the new paradigm, the principle of social responsibility involves the vehicle manufacturer providing crash protection inside and outside the vehicle". (World Health Organization – World report on road traffic injury prevention).

Based on the previously analyzed aspects it can be concluded that there are high probabilities of surviving a road crash without serious damage as long as:

- no direct impacts are received in any part of the body.
- no high accelerations are undergone during relatively long periods of time.

Modern vehicles are provided with an array of safety devices that aim at assuring the above conditions. These devices can be segmented into three groups, according to their moment of acting within the sequence of the traffic impact event:

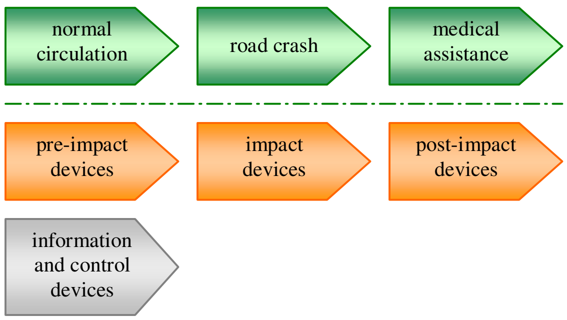


Figure 10. Segmentation of safety devices according to their moment of acting within the sequence of the traffic impact event.

The next important aspects to point out about the bases of impact safety in side road crashes are:

- firstly, it is well known that pedestrian protection is not a minor issue. Once again it has to be remembered that 90% of road fatalities take place in low-income or medium-income countries, the vast majority of the victims being pedestrians, cyclists or motorcyclists. However, it can be argued that the most frequent initial point of impact for these crashes is the frontal sector of the vehicle, an aspect of road safety that is not being discussed in this paper. Therefore, considering that few collisions against pedestrian involve the side section of the motor vehicle –e.g.: 4% of pedestrian deaths in the United States are due to crashes where the side of the vehicle is the initial point of impact (2)–, everything that is going to be stated in this paper refers to the protection of the occupants of a motor vehicle.
- secondly, the vast majority of road impacts involve automobiles and light-trucks (including SUVs) –e.g.: 94% of all types of crashes and 82% of fatal crashes in the United States involve either automobiles or light trucks (2)–. So, the bases herein discussed refer to the named types of vehicles. Yet, most of the aspects analyzed can be applied not only to such types of vehicles, but also to others as large trucks or buses, with the exception of motorcycles, since this type of motor vehicle lacks the minimum protection that is needed to overcome unharmed any kind of traffic crash, as it is often confirmed by the fatalities statistics.
- lastly, information devices (xenon cornering lamps, high-mounted stop lamps, tyre-pressure monitoring, etc.) and control devices (anti-lock braking systems, electronic stability management, etc.) are considered to perform their functions adequately; additionally, they are related to the prevention of a road crash. Consequently, the feasible innovations regarding these devices are not discussed here.

Deeming these aspects, what follows is a general review of the main functions that safety devices should perform before, during and after a traffic impact, in order to enhance the probabilities of surviving undamaged from a traffic impact as regards the occupants of either automobiles or light-trucks.

To begin with, it can be argued that in a traffic accident a little more than a second is the time that mediates between the instant of the first impact and the complete stop of the vehicle (depending on the initial speed, mass of the automobile and stiffness coefficient, among others). In several NCAP frontal-impact tests it can be observed that the driver's head impacts the airbag after around 1/10th of a second, indicating that the period of time available for safety countermeasures is infinitesimal. In this context, every action aiming at increasing the protection offered to automobilists which can be performed before the actual accident happens will bring great benefits. Therefore, the function proposed for the pre-impact devices are the following:

- control the perfect operation and use of the safety devices, and perform the necessary actions to assure both of them.
- pick up and process the necessary information so that the safety devices can act during the impact.
- establish the "injury potential" (mainly through the circulation speed) and adjust the configuration of the vehicle according to each circumstance.

The mentioned actions, all of which can be performed while the vehicle is circulating normally, will allow a better performance for the safety devices. As an example of the advantages of the first function, the assurance of the use of the seatbelt by every motorist can be named, since this action will not only protect the restricted occupant but also the other occupants, as an unbelted person may hit others in the vehicle, possibly damaging them in a serious way. This control should lead both to "informative" actions (as most modern vehicles perform) as well as direct actions such as the elimination of the possibility of circulation if any of the occupants of the vehicle does not have his seatbelt buckled up. In the second proposed function, the efficiency of the safety devices will be incremented, since elements such as the air-bag, the pre-tensioner or the load-limiter will be able to adapt their response according to the occupant's weight, size, and impact speed and direction. These named physical phenomena and their values must be measured and stored during normal circulation, and be ready to be used as inputs in the event of a road crash. Lastly, the third function proposed allows changes in some of the settings of particular devices while speed increases. In this way, for instance, the pre-tensioner of the seatbelt can begin to exert a certain amount of pressure as the vehicle travels faster, anticipating the necessary actions in case of a road crash (which will be thus less violent) and also letting the driver know that he is stepping into a more dangerous level of “injury potential”.

On the other hand, the functions that impact safety devices should perform are simply defined by the aspects briefly discussed in the last section (avoid both direct impacts and dangerous accelerations):

- maintain the structural integrity of the occupants' vital volume, assuring enough survival space to avoid any direct impacts.
- avoid the penetration of objects to the occupants' vital volume.
- absorb the whole kinetic energy both of the vehicle and of the occupants (to avoid elastic-type crashes or instantaneous changes of speed), maintaining the deceleration within safe levels.
- avoid any contact with the potentially dangerous surfaces of the interior of the vehicle.

Finally, it must be highlighted that after the road impact takes place, it is vitally important to provide medical assistance to the victims as soon as possible. There are some modern vehicles that are equipped with a combination of GPS and mobile communication devices, supported by a 24-hour emergency center that when an impact is detected is capable of assisting the occupants and alerting the emergency medical service, giving them the precise position of the vehicle. Yet, it is very important that while the emergency medical service gets to the road crash site the occupants be protected from fire, noxious gases or other impact-related dangerous phenomena. It is worth mentioning that fire occurrence is not frequent in a road crash, but when it does occur it represents a very dangerous phenomenon –fire occurrence crashes bear 0,1% of total road crashes in the United States whereas they represent 2,8% of fatal crashes (2)–. Finally, it is also particularly important to assure that the emergency medical service is able to assist the victims without losing precious time in extracting the occupants from the deformed vehicle (it can be stated that in many high-speed road crashes the external structure and the compartment deform in such a way that occupants can be extracted only with the use of specific cutting machines, a kind of action that can last even hours). Therefore, the following functions proposed for post-impact devices complete the bases for side impact safety:

- warn the nearest medical care services.
- protect the occupants in case of a fire taking place, from noxious gases or other impact-related dangerous phenomena.
- allow the quick extraction of the victims to be assisted.

To conclude, it is important to point out that the bases of side safety recently stated can be extended to frontal and rear impact, given their general approach to the mechanisms of injury, human tolerance aspects, and the ways to overcome the potential dangers involved in a side road crash.

ANALYSIS OF THE PROTECTION OFFERED BY CURRENT SIDE SAFETY DEVICES

In the last section the bases of side impact safety have been established and segmented into the ones pre-impact, impact, and post-impact devices should perform. In this section, the stated functions will be assigned to the vehicle functional groups, so as to facilitate the identification of the feasible innovation as regards each component. The groups considered are: automation devices; compartment and interior structure; external structure; restrain devices.

Thus, the analysis of the protection offered by current safety devices will be compared to the functions they should perform, grouped in the indicated way.

Automation devices analysis

This includes all of the electronically based equipment, including sensors, communication devices, and the corresponding software and hardware. The bases of side impact safety that apply for this group include the following:

Table 2.
Summary of main functions of the side safety devices grouped in the automation devices.

traffic impact sequence	function
normal circulation	– control the perfect operation and use of the safety devices, and perform the necessary actions to assure both of them. – pick up and process the necessary information so that the safety devices can act during the impact.
road crash	– (none)
medical assistance	– warn the nearest medical care services.

As regards this functional group, the next improvement opportunities can be highlighted:

- most modern vehicles indicate when seatbelts are not buckled up, but no direct action is performed if the vehicle is moving with a non-restrained passenger. Given the danger associated with this situation, and from a strictly safety point of view, circulation should be permitted only if every occupant is correctly buckled up.
- modern technology allows to measure the position of the head, shoulders, and other parts of the body, and their relative location regarding relevant elements, such as the headrest, to assure that the safest position is set. Modern technology also allows to modify the interior of the vehicle (namely the seats and seatbelt anchorages heights) if the conditions are not the fittest.
- most safety devices (such as the pre-tensioner, the load limiter or the airbags) act according to default parameters, disregarding the vital real information that would greatly foster their efficiency.
- the majority of modern vehicles lack the already developed technology that automatically warns the nearest emergency medical service, and provides the exact location of the vehicle.

Compartment and interior structure analysis

This segment groups all of the components immediately surrounding the occupants, such as the passenger cell, side door beams, A and B pillars, etc. Therefore, the bases regarding them are:

Table 3.
Summary of main functions of the side safety devices grouped in the compartment and interior structure.

traffic impact sequence	function
normal circulation	– adjust the configuration of the compartment and interior structure according to the defined "injury potential".
road crash	– maintain the structural integrity of the occupants' vital volume, assuring enough survival space to avoid any direct impacts. – avoid the penetration of objects to the occupants' vital volume. – avoid any contact with the potentially dangerous surfaces of the interior of the vehicle.
medical assistance	– protect the occupants in case of a fire taking place, from noxious gases or other impact-related dangerous phenomena. – allow the quick extraction of the victims to be assisted.

The next improvement concerning the compartment and interior structure can be pointed out:

- no modification of the circulation condition takes place as speed increments. An example of this can be considered: as the vehicle gains speed all the seats should adjust themselves to the most favorable position regarding impact safety.
- impact tests and empirical evidence show that the passenger cell suffers relevant deformation, even at arguably low-speed crashes, leading to direct impacts to the occupants. On top of that, the compartment is frequently unable to prevent the penetration of external objects through the door panels or, specially, through the fragile side windows.
- the A and B pillars offer hard and thus potentially harming surfaces, as the roof does (it is worth mentioning that use of glass roofs lacking shock absorbing materials is more and more common every time). In real-world side crashes all of the named interior elements can be hit by the occupants as a result of a combination of rotation movements following the impact.
- there is no safety device prepared to prevent a fire from extending into the occupants' survival space. What is worse, most of the interior surfaces are capable of easily catching fire while at the same time they offer relevant resistance to extinguishing actions.
- compartment deformation generally affects seriously the possibility of extracting rapidly the passengers in a negative way, reducing their probability of survival.

External structure analysis

This analysis is directed towards the crushable zones of the vehicle that receive the direct impact of the road crash, and which safety bases are stated as:

Table 4.
Summary of main functions of the side safety devices grouped in the external structure.

traffic impact sequence	function
normal circulation	– adjust the configuration of the exterior structure according to the defined "injury potential".
road crash	– absorb the whole kinetic energy of the vehicle, maintaining the deceleration within safe levels.
medical assistance	– allow the quick extraction of the victims to be assisted.

In this case the improvement opportunities are the following:

- no modification of the circulation condition takes place as "injury potential" is altered. An example of this may be the modification of the stiffness coefficient with the real mass of the vehicle. It must be remembered that the NHTSA states that frontal crash test results can only be compared to other vehicles whose weight is plus or minus 115 kg. Thus, it can be argued that in a side crash against a fixed object a vehicle transporting only the driver behaves in a different way than when transporting five passengers and baggage.
- as analyzed in the introduction, the side external structure is capable of absorbing an extremely low amount of kinetic energy, allowing the remnant energy to deform the passengers' compartment dangerously. Additionally, it can be argued that at high-speed impacts, and after a great amount of compartment intrusion takes place, the increased rigidity of the cockpit will probably generate an elastic-type collision, leading to extremely high and dangerous acceleration phenomena.
- for the same reasons stated above, significant structure and compartment deformation make the extraction of the injured occupants utterly difficult.

EXAMPLE BOX 3

Two examples of relevant compartment intrusion in side crashes leading to direct impacts to occupants

The following photograph shows the extent of lateral compartment intrusion sustained by a small car when it is hit on its side. It is worth pointing out that the striking vehicle bears only minor deformation of the frontal structure:

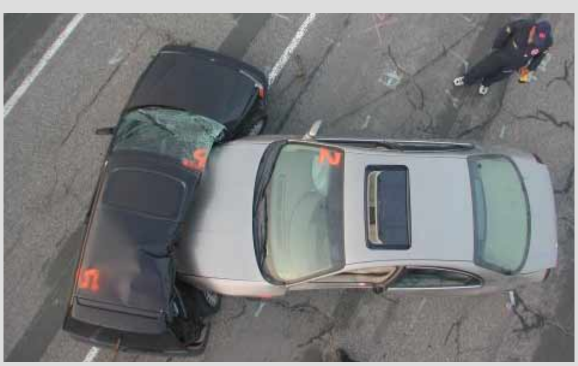


Figure 11. Compartment intrusion in a car-to-car side impact.

Source: reference 9

Similarly, the next picture of a pole test conducted by the European New Car Assessment Program shows a considerable amount of lateral intrusion in an impact at 50 km/h, with the pole entering the compartment and occupying most of the driver's original position, throwing him towards the other occupant who will be moving in the opposite sense:

Figure 12. Compartment intrusion in a pole side impact test for a 5-star rated automobile (Renault Velsatis).

Source: reference 10

Restrain devices analysis

The group of restrain devices includes the seatbelts and the airbags (considered as SRS – Supplementary Restraint System– devices) and are related to the following safety bases:

Table 5.
Summary of main functions of the side safety devices grouped in the restrain devices.

traffic impact sequence	function
normal circulation	– adjust the configuration of the restrain devices according to the defined "injury potential".
road crash	– absorb the whole kinetic energy of the occupants, maintaining the deceleration within safe levels. – avoid any contact with the potentially dangerous surfaces of the interior of the vehicle.
medical assistance	– allow the quick extraction of the victims to be assisted.

Considering these devices, the relevant improvement opportunities are:

- no modification of the circulation condition takes place as the vehicle gains speed. An example of this was already mentioned (an in-

crease of the pressure of the pre-tensioner as speed increments should lead to less violent actions in case the crash happens).
- three-point seatbelts are designed to act efficiently in full-lap frontal impacts. Yet, in side crashes, the far-side occupant is launched towards the near-side occupant, since the three-point seatbelt is unable to prevent this movement. On the other hand, compartment intrusion may cause the near-side occupant to be pushed towards the far-side occupant (who is moving in the opposite direction).
- there is no restrain for the relative movement between the head and the body (a kind of action that can be extremely harmful as explained before). On top of that, the head which is highly susceptible to direct impacts may hit dangerous interior surfaces such as A or B pillars. An available safety device that suits this purpose is the H.A.N.S. (Head and Neck Support System) device used in motor racing, but which permanent use will surely be considered a major nuisance.
- there is no restrain for the extremities. As mentioned before, unrestrained arms have the capacity of striking and damaging seriously the other occupants of the vehicle.
- every action performed by the restrain devices will be more efficient if their response could vary according to the real parameters previously measured and processed, a kind of characteristic that most restrain devices are not provided with.
- once the crash is over, a device that permits the disengagement of all restraint devices (even form the outside of the vehicle) would be of great help to quickly extract the occupants, considering that some of them could be unconscious and unable to liberate their seatbelts.

Section conclusion

To conclude, all of the improvement opportunities mentioned above should improve the protection offered by current side safety devices, yet they must be further analyzed thoroughly within the corresponding settings and using the appropriate resources. But if it is assumed that these improvements are possible to be introduced in modern vehicle from the technical, industrial and financial points of view, they may lead to the following feasible innovations.

FEASIBLE INNOVATIONS FOR SIDE ROAD CRASHES

The automobile revolution started more than a hundred years ago. Until these days, it has redesigned itself hundreds of times, and it has redesigned along its phenomenal development the way in which the world looks, and the lives of the people that live there. Regarding this paper, hundreds of thousand technicians, engineers and experts struggled over those years to develop literally millions of devices that assure the generation of the necessary power, the efficient movement and control, the adequate resistance to transport both the occupants and their loads, and the suitable reliability and a contained operation cost, among many other necessities. So it can be argued that most of the feasible technical solutions involving automobiles have been already introduced or discarded.

Yet, periodically, some ideas (probably discarded in less favorable conditions) arise and consolidate as valid new options. As a recent example, in the 2005 Detroit Auto Show Honda surprised everyone by introducing the new Ridgeline pick-up bearing a lockable, weather-tight space under the rear cargo floor, a simple device no other pick-up showed in their 80-years history. Therefore, the innovations that will be next introduced are intended to act as a starting point for a thorough analysis of their feasibility, considering that they have been studied in a general and synergistic way, considering that they consist mainly on improvements of already existent devices or on the reengineering of them, and considering that they have been conceived under the precept that rather than making a successful automobile safe it is highly preferable to transform a safe vehicle into a successful one.

Innovations in the compartment and interior structure

As for the innovations in the compartment of the automobile, the following are proposed:
- the elimination of the possibility of sliding down the side windows, while the car is moving.
- a rigid cockpit capable of maintaining its shape in high-speed impacts (using materials and a body framework with more mechanical stiffness, including a more resistant shape as the ellipsoid one).
- an increase in the resistance to impacts of the side windows while keeping approximately the actual mass (e.g.: glass laminated with polycarbonate).
- the establishment of a protection barrier against a fire produced at the exterior of the compartment that could endanger the occupants.
- the provision of a breathable atmosphere inside the compartment until the moment of the rescue of the victims of the crash.
- the provision of different options for the occupants' extraction, not only including the doors but also all the glass surfaces that should slip inside the rigid compartment, with a mechanism

able to be activated either from the interior or the exterior of the vehicle.

Innovations in the external structure

The feasible innovations in the external structure are:

- the increase of the length of the side sectors of the car, leading to higher levels of kinetic energy that can be absorbed .

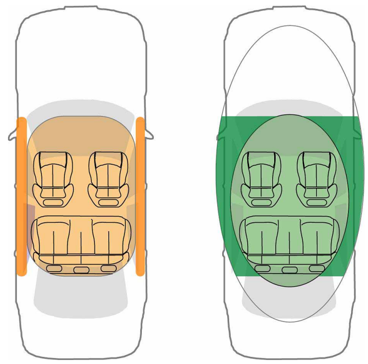


Figure 13. Comparison between current length of external structure (left) and a structure with increased length (right). The latter is also combined with an ellipsoid compartment .

- the establishment of areas with different stiffness coefficients according to the length of the structure, the mass of the vehicle, and the maximum probable impact speed.
- the multiplication of the areas with different stiffness coefficients as to improve the continuity of the structure.
- a homogeneous behavior of the collapsible area (and therefore the lack of mechanical elements or external objects such as baggage).
- the variation of the stiffness coefficient according to the variation of the mass of the vehicle.

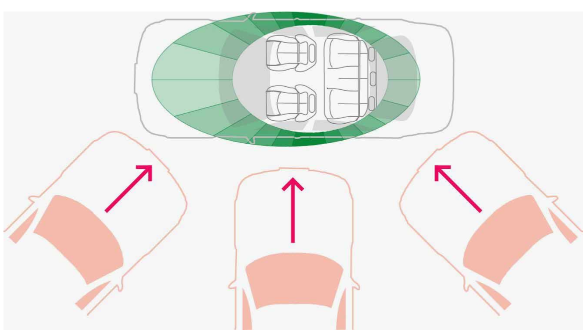


Figure 14. An external structure bearing multiple areas of different stiffness coefficients, and a homogeneous behavior of the collapsible area will absorb kinetic energy more efficiently.

Innovations in the restrain devices

As regards the innovations in the restrain devices the improvements consist of:

- the adaptation of the interior of the automobile in order to offer the occupant the safest position.
- the progressive increase of the seat belt tension along with greater speeds.
- the provision of four-point seat belts for all the occupants.
- the improvement of the pre-tensioner and of the load limiter so that they can act according to the parameters measured previously or during the accident.
- the provision of an inflatable device similar to the H.A.N.S. adjoined to the seatbelt that acts only in the case of an accident.

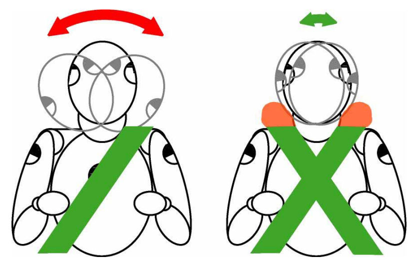


Figure 15. Current safety devices do not prevent dangerous lateral movements of the head (left) which could be minimized by the combination of a four-point seatbelt and an inflatable device similar to the H.A.N.S that acts only in the case of an accident (right).

- the provision of a restraint device for the extremities (arms and legs).
- the development of central and external disengagement mechanisms for the restraint devices that should be operative immediately after the road crash.

Innovations in the interior structure

The following innovations in the interior structure of the automobile are proposed:

- the provision of electromagnetic mechanisms which should be completely collapsible and able to move away from the occupants in the crash (as an example, the possibility of forwarding the steering-wheel will eliminate the possibility of the head impacting it, and make the driver airbag unnecessary).
- a larger space between the occupants and the potentially dangerous objects.

Figure 16. The Hy-wire concept car by General Motors proposes an interior structure that bears a large space between the occupants and the potentially dangerous objects by using electromagnetic mechanisms.

Source: reference 11

- the provision of lateral airbags in the windows (with a somehow different function from the current one, since they should cover the whole surface in the minimum possible time to avoid direct impacts).
- an important increase of the capacity to offer soft surfaces where there are potential points of contact (including the roof).
- the elimination of all combustible materials of the interior of the vehicle.

Integral design

Finally, when thinking about an integral design the way to satisfy the driver's basic necessities can be analyzed as a whole, among which impact safety and protection of the environment should occupy a preponderant place, adding the following ones to the previous innovations:

- the measurement of all the parameters for the correct performance of the safety devices; the elimination of the possibility of circulation if any safety device does not work properly, it is misused or not used at all (e.g.: any of the occupants of the vehicle does not have his seatbelt buckled up); and the warning to the nearest medical care services indicating the exact location of the crashed vehicle.
- the generation of power and its transmission by means of four electric engines, one in each wheel (reducing the volume destined to the engine and transmission and allowing larger spaces destined to the absorption of kinetic energy while maintaining the current overall dimensions).
- the placing of the energy source under the cockpit (this generates both a lower center of mass and no increase in length or width).
- the increment of the wheels' diameter (this provides the vehicle with a smaller tendency to overturn and it allows to increase the height of the center of mass without affecting the stability).
- speed management through a mandatory intelligent speed adaptation system, which integrates GPS arrays, road and speed limits digital databases, and in-vehicle currently available hardware and software (namely on-board computer, speed limiter, and cruise control) that will help to reduce circulation speeds to comply with the legal limits, or even better, to remain within safe limits.

Section conclusion

To conclude, it has to be pointed out that the intention of this paper is to present the feasible innovations, without being thoroughly described, as a compendium of integrated ideas that should be analyzed from a technological, industrial, and economical point of view in order to determine whether they can be introduced in modern vehicles or not. As mentioned before, this work has been done with the idea that rather than making a successful automobile safe it is highly preferable to transform a safe vehicle into a successful one, and bearing in mind that safer cars will produce lower quantities of road victims, and will probably bring higher profits to the carmaker that is able to successfully sell the feasible innovations.

SELLING SAFETY INNOVATIONS

"The world's first automobile to be built with the safety of the occupants as the sole design objective was unveiled in New York by Liberty Mutual Insurance Company and Cornell Aeronautical Laboratory Inc. who designed and built the car in a joint undertaking". (The safest car in the world – Safety maintenance and Best's insurance news – 1959).

Selling safety innovations has always been a very sensitive issue. Even nowadays, when there is greater awareness of the benefits of having and using as many safety devices as possible, some people refuse to use their seatbelts, which have proven to be one of the most useful safety devices ever introduced in automobiles. Furthermore, many among the "rebels" show neither oblivion nor lack of awareness in their behavior; instead, they show resentfulness. They feel that using seatbelts is an annoying imposition conceived to make their lives miserable, stealing them away the pleasure of driving their automobiles freely, a sensation strongly associated with the ideas of freedom, individuality and prosperity. So they simply and rationally refuse to buckle up. This gives a hint about the reason why 4-point seatbelts (which have demonstrated to offer a more efficient protection than 3-point seatbelts, but which are less comfortable) are not offered even as an optional in current automobiles. Another example that shows how unpopular road safety is can be found in every Motor Show around the world where all kinds of new technical solutions burble in dozens of concept cars whereas the last concept vehicle designed with the safety of the occupants as the sole design objective is the Volvo SCC that dates far back to 2001.

To conclude this very concise discussion about the selling of the safety innovations, it can be stated that it is a very difficult target to achieve (even considering the mentioned present greater awareness and the great economic and social benefits that safer cars would imply), and that automobile history demonstrates that safety innovations have not had a great success, unless they have been introduced in the high-volume automobiles, particularly those more prestigious, so that the innovations are perceived as an added value not as a pernicious imposition, dragging in this way the consumer to desire the most sophisticated devices available.

CONCLUSIONS

"The uncertainty of human behavior in a complex traffic environment means that it is unrealistic to expect that all crashes can be prevented". (World Health Organization – World report on road traffic injury prevention).

Side impacts kill. So do frontal impacts, rear impacts, rollovers and other manners of traffic collision which as a whole generate more than a million deaths every year. Yet, road crashes and their consequences result from an extremely complex combination of aspects involving government, industry and individual users, thus any effective response will necessarily require a large mobilization of effort by all those concerned at the international, national, and local levels. The wider and more synergistic approach to the global challenge of reducing traffic casualties, the more effective the results and the faster the benefits. Similarly, great advantages should be found when a safe automobile design is thought as a whole and every aspect is deemed in a general and synergistic way. On the other hand, when only partial improvements are added, better safety than current one would also be achieved, although this would happen over a longer period of time, and would probably be less efficient.

This paper proposed a general and synergistic approach, analyzing firstly and briefly the mechanisms of injury and biological resistance, after what it was concluded that direct impacts should be avoided at most parts of the body, specially at the head, neck and spinal cord, chest, and abdomen; and it was also concluded that high levels of acceleration can be safely undergone, provided that they are exerted over extremely short periods of time, that they coincide with favorable directions and senses, and that they are not combined with direct impacts phenomena. Secondly, the bases of side safety were established, aiming at avoiding direct impacts and harmful accelerations, but also at setting the fittest conditions before the crash, and at allowing fast and efficient medical attention after it. Thirdly, the improvement opportunities of current safety devices were studied, and this lead to a series of feasible innovations, aiming at enhancing the protection that an automobile offers to their occupants in case of a side crash, and that should be further analyzed within the corresponding settings and using the appropriate resources. Yet, most of the aspects discussed can be easily translated to other types of road crashes. Lastly, some comments about the ways in which the feasible safety innovations should be marketed were argued, considering that selling this type of devices has always been a very difficult and sensitive issue.

To conclude, everything herein stated is intended to provide several starting points for future developments, based either on improvements of available safety devices or on their reengineering; to highlight those starting points as the conclusion of a general and synergistic analysis; to encourage the people working to protect automobile passengers sustaining a side impact every time in a more efficient way; to help assuring that side impacts stop killing.

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